NATURAL FREQUENCIES EVALUATION ON EXISTING REINFORCED CONCRETE BRIDGES USING MICROTREMOR TESTING

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For my beloved father Idris Kasim, my mother Robiah Ujang,
my lovely husband, brother and sisters.
Thank you for your supports and always being there for me along my journey to complete this thesis. Without you all, I can't have achieve successful life and become better person.

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ABSTRACT

Most bridges in Malaysia do not take earthquake loadings into their structural design consideration. Structure constructed without the consideration of seismic design is generally more vulnerable to ground shaking during seismic event. Even though Malaysia is located on the stable Sunda shelf with low to medium seismic activity level, effects of tremors due to Sumatran earthquakes have been reported several times. Identification of natural frequencies is important to avoid bridge resonance which could happen when frequency of excitation coincides with a bridge natural frequency. Resonance can cause failure to bridges. Therefore, it is important for newly constructed and old bridges to be tested using simple dynamic test such as microtremor test in order to determine the natural frequencies of the bridges. Microtremor is also known as ambient vibration test. The test is a non-destructive test and easy to be conducted with less labor, time and cost. From the testing, 'ambient' vibration excitation experienced by a structure under normal operating conditions can be determined. The aim of this study was to determine the natural frequencies of two different lengths of reinforced concrete bridges crossing Sungai Sembrong and Sungai Simpang Kiri. By using GEOPSY software, Fourier Spectra Amplitude Ratio (FSA) analysis used for determining bridge natural frequencies and Horizontal-To-Vertical-Spectra-Ratio (HVSR) analysis for ground natural frequencies, *fo.* The natural frequency results for Sungai Sembrong Bridge (70 meter) was 2.2 Hz and for Sungai Simpang Kiri Bridge (75 meter) was 2.0 Hz, while the ground natural frequencies were 1.4 Hz to 2.1 Hz at Sungai Sembrong and 1.0 Hz to 1.5 Hz at Sungai Simpang Kiri. The frequency values for both bridges were almost the same. The bridge with longer span length had a lower frequency value compared to the one with shorter span. The frequency results were verified by calculating and developing empirical equation from previous researchers and code of practice.

ABSTRAK

Kebanyakkan jambatan di Malaysia tidak mengambil kira beban gempa dalam rekabentuk struktur. Struktur yang direkabentuk tanpa mengambil kira beban seismik adalah lebih terdedah kepada gegaran tanah semasa kejadian seismik. Walaupun Malaysia terletak di kepulauan Sunda yang stabil dimana tahap aktiviti seismik pada kadar rendah ke sederhana, namun kesan gegaran akibat gempa bumi Sumatera telah dilaporkan beberapa kali. Penentuan kekerapan semulajadi adalah penting untuk mengelakkan resonant keatas jambatan yang berlaku apabila nilai frekuensi pengujaan bersamaan dengan frekuensi kekerapan semulajadi. Resonant boleh menyebabkan jambatan gagal berfungsi Oleh itu, adalah amat penting untuk menjalankan ujian dinamik seperti ujian mikrotremor ke atas jambatan sedia ada dan baru bagi menentukan frekuensi semulajadi. Ujian mikrotremor juga dikenali sebagai ujian gegaran ambient. Ujian ini mudah dijalankan menggunakan tenaga kerja, masa serta kos yang rendah. Melalui ujian ini gegaran 'ambient' yang dikenalpasti oleh struktur adalah dalam keadaan operasi normal. Tujuan kajian ini untuk mengenalpasti frekuensi semulajadi keatas dua jambatan konkrit tetulang yang mempunyai panjang rentang yang berbeza iaitu jambatan Sungai Sembrong dan Sungai Simpang Kiri. Dengan menggunakan perisian GEOPSY, analisis Nisbah Spektra Fourier, frekuensi semulajadi jambatan telah dikenalpasti.Manakala analisis Nisbah Spektra Mendatar dan Menegak untuk penentuan freqkuensi semulajadi tanah. Frekuensi semulajadi bagi jambatan Sungai Sembrong (70meter) adalah 2.2Hz manakala jambatan Sungai Simpang Kiri (75meter) adalah 2.0Hz. Frekuensi semulajadi tanah adalah antara 1.4Hz hingga 2.1Hz bagi Sungai Sembrong, manakala bagi jambatan Sungai Simpang adalah 1.0Hz hingga 1.5Hz.Frequensi semulajadi bagi kedua-dua jambatan hampir sama. Jambatan yang mempunyai panjang rentang lebih panjang mempunyai frekuensi yang rendah berbanding panjang rentang yang kurang. Keputusan bacaan frequensi jambatan disemak menggunakan mengiraan, persamaan daripada pengkaji-pengkali terdahulu dan juga standard.

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Ao	-	Average amplitude
EW	-	East-West
f	-	Frequency in Hertz
fo	-	Ground natural frequency
Fo	-	Bridge natural frequency
FEM	-	Finite Element Modeling
FFT	-	Fast Fourier Transform
FSA	-	Fourier Spectral Amplitude
GEOPSY	-	Geophysical Signal Database for Noise Array Processing
H	-	Height
HVSR	-	Horizontal-To-Vertical Spectra Ratio
JPS	-	Jabatan Pengairan dan Saliran
JKR	-	Jabatan Kerja Raya
k	-	Stiffness
L	-	Length
m	-	Mass
m	-	Meter

NS	-	North-South
RC	-	Reinforced Concrete
SDOF	-	Single degree of freedom
SSI	-	Stochastic Subspace Identification
T	-	Fundamental period (second)
t	-	Time
UD	-	Vertical direction
Üg	-	Ground acceleration

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Bridge is one of the important structures in civil engineering field as a facility used in daily life. A bridge is built to overcome physical obstacles such as a body of water, valley or road for the purpose of providing passage over the obstacles. Previous earthquakes in Loma Prieta, USA (1989), Kobe, Japan (1995), Izmit, Turkey (1999), Chi-chi, Taiwan (1999) showed results of extensive damages to transportation facilities. The results also showed that bridges could be vulnerable structures under dynamic loading (Kibboua & Farsi, 2008). Such damages not only capture specialist's attention to the seismic risk to the bridges but also revealed the need to address various critical issues in seismic design and strengthen of existing bridges (Ren, Zatar & Harik, 2003).

Most bridges in Malaysia were constructed using reinforced concrete. These bridges were designed according to the British Standard without seismic consideration. Structures constructed without consideration of seismic loading are highly prone to damages when facing earthquake. On the other hand structures constructed with seismic loading, have minimal level of risk of damage. Many countries situated in a high seismic region such as Japan has considered earthquake loading in their structural design including bridges by applying seismic code.

There are many important factors to be considered to construct a bridge such as dynamic loading, wind and earthquake. Lack of such consideration and information can put the bridge in dangerous situation that will not only affect the structure but also to the public users. It is important to ensure an adequate level of safety for both new and existing large span bridges against dynamics loadings such as traffic, wind and earthquake (Ren, Peng & Lin, 2005).

One of the parameters used for seismic code is fundamental frequencies which is also one of the parameters in dynamic characteristic. Dynamic characteristic is the behavior of the bridge without external forces including natural frequencies, mode shape and damping. Identification of bridge natural frequencies is important to monitor resonance phenomena. Thus, it is important to know the natural frequency of the system and frequencies at which excitation is likely to occur and keep separate (Panikkar, N., 2015). This can be done by conducting microtremor testing on the existing bridges. For both newly constructed bridges and older bridges, it is desirable to measure the dynamic characteristics (resonant frequencies, mode shapes and modal damping) of the bridges to have a better understanding of their dynamic behavior under normal traffic loads as well as extreme loads such as those caused by seismic events or high winds (Farrar & James, 1997).

Microtremor test is used for determining dynamic characteristics by measuring the vibration behavior of a structure. This is by recording, evaluating and interpreting under ambient influences without artificial excitation, by means of highly sensitive acceleration sensor (Wenzel & Pichler, 2005). This test is inexpensive since no equipment is needed to exciting the bridge. Microtremor measurement corresponds to the real operating condition of the bridge. There is no interruption of the traffic while conducting the test. This test were successfully applied to several large scale cable-supported bridges, such as the Golden Gate Bridge, Bosphorus Suspension Bridge, Deer Isle Bridge, Quincy Bayview Bridge, Tsing Ma Suspension Bridge, Kap Shui Mun Cable-Stayed Bridge, Maysville Cable-Stayed Bridge and Roebling Suspension bridge (Ren *et al.*, 2005).

This study used microtremor test in order to evaluate bridge natural frequencies. By using portable devices natural frequencies evaluation has become easier and faster. This study was a preliminary dynamic assessment and as a dynamic record of existing bridges in Malaysia. The frequency values can also be used for seismic design in future. By knowing frequency, seismic loading can be determined. This information is important to know the safety level of the bridges when facing earthquakes.

1.2 Problem statements

Malaysia is situated on a stable sunda shelf with a low to medium seismic activity level However, the effects of tremors from Sumatra earthquakes have been reported several times. For example, the First Penang Bridge experienced some minor damages due to the Acheh earthquake on 24 December 2004 (Meldi, 2011). Most bridges in Malaysia did not include earthquake loadings into their structural design consideration (Adnan, Suhatril & Mohd Taib, 2008). Structures constructed without the consideration of seismic design are generally more vulnerable to ground shaking during seismic events (Kong & Won, 2005).

During earthquakes potential soil structure resonance can be predicted by knowing the structure and ground natural frequency. When the frequency content of the ground motion shifts in a similar manner as the natural frequencies of the structural response, a phenomenon referred known as a moving resonance takes place (Eatherton & Naga, 2012). Risk of resonance arises when the excitation frequency of the loading or a multiple of it coincides with a natural frequency of the bridge structure. When resonance occurs, the dynamic response of the structure increases very rapidly (Bjorklund, 2004). Determining the natural frequency is important in order to avoid risk of resonance.

Identification of the natural frequency is related to the mass and stiffness of the bridges. The frequency is an essential parameter to describe the vibrating behavior of the bridges. The natural frequencies of the bridge are identified in order to know vibration mode shape for each natural frequency respond to the deflected shape when the structure is vibrating at that frequency (Salawu, 1995). Therefore, it is important to conduct testing on the existing bridge.

From microtremor test, the natural frequencies can be identified. Many researchers used accelerometer and seismometer sensor in their studies. Majority of the researchers used accelerometer rather than seismometer. Seismometer is regularly used to identify fundamental frequencies of soils. The use of seismometer is then expanded to the identification of fundamental frequencies of structure by locating the seismometer on top of a building with a minimum of three readings are recorded.

There has been a lack of previous study on ambient vibration using seismometer on the bridge. Therefore, this study was conducted to identify the natural frequencies of bridges by using three units of 1 Hz seismometer sensors. Chatelain *et al*.(2004) also used seismometer to identify natural frequencies of bridges. Two types of reinforced concrete bridges with different lengths were selected for the preliminary dynamic assessment. Both bridges were also located at areas with the same soil type for an easier identification of fundamental frequency.

1.3 Objectives

The objectives of this study were as follow:

1. To determine the natural frequencies and mode of vibration for simple concrete beam bridges by using microtremor test.
2. To identify ground frequencies of the bridges.
3. To verify the prediction of the first natural frequency against manual calculation, previous empirical relationships and code of practices.

1.4 Scope of study

The scope of this study can be summarized as follows:

1. Microtremor test were conducted on two reinforced concrete beam bridges located in Batu Pahat, Johor which were Sungai Sembrong and Sungai Simpang Kiri Bridge. Both bridges are three spans with different length. For this study bridge length limited from 70 meters to 75 meters.
2. Microtremor test were conducted on the bridge deck and ground area in order to identify the bridge natural frequencies.
3. Microtremor signals were recorded using three units of 1 Hz Lennartz-Triaxial seismometers. The sensors captured the signals in three directions which were North-South (NS), East-West (EW) and Vertical (UD).
4. Vibration data were processed using GEOPSY (Geophysical Signal Database for Noise Array Processing) software by applying Fourier Spectra Ratio Analysis for in determining bridges natural frequency and Horizontal-To-Vertical Spectra Ratio Analysis for ground natural frequency.

Finally, bridges natural frequency was verified by calculating and developing empirical equation from previous researchers and code of practice. The bridges frequencies from microtremor test were also compared with a companion's study who modeled the same bridge using finite element modeling.

1.5 Significance of study

Frequency of each structure should not be within the range of ground frequency in order to avoid resonance from happening especially during earthquakes. Soil-structure resonance can exacerbate response of a structure when the fundamental frequency of the structure coincides with the predominant frequency of ground on which the structure is founded (Koong & Won, 2005).

During resonance, structure will vibrate in the same frequency of the ground. This will create an uncontrolled condition and may cause damages to the bridge structure such as cracks or more worse could lead the bridge to collapse. It is thus important, to know the natural frequency of the system and the frequencies at which excitation is likely to occur to keep them separate (Panikkar, 2015). The frequency values can also be used for seismic design in future. Determining the natural frequency of existing bridges also can give a dynamic record that will assist its' preservation.

1.6 Research outline

Chapter 2 provides a literature review of concrete bridges, ambient vibration sources, examples of bridge failures due to earthquake, introduction to microtremor test, dynamic behavior of bridge structures in term of natural frequency and analysis used in this study and critical reviews on previous research.

Chapter 3 provides information on research methodology, including pre-measurement, measurement and post-measurement. The pre-measurement consists of desk study and site visit, while the measurement stage explains about microtremor test procedures and position of sensor during testing. The post-measurement explains microtremor data collection.

Chapter 4 discusses microtremor test results from both bridges. Dynamic characteristics of the bridges in terms of natural frequency were identified. The first natural frequency was verified by calculating and developing empirical equation from previous research and code of practice. The frequency was also compared the frequency discovered in a companion's study on the same bridge using finite element modeling results.

Chapter 5 concludes all main findings from this study and recommendations for future study.

CHAPTER 2

LITERATURE REVIEWS

2.1 Introduction

This chapter presents an overview of concrete bridges, bridge failure due to earthquakes, ambient vibration sources, and introduction on microtremor test, dynamic behavior of bridge, analysis used in this study and critical review from previous research.

2.2 Overview of concrete bridges

Bridge is a structure that carries the road traffic or other moving loads over a depression or obstruction such as channel, road or railway. Bridge structure comprises three components including superstructure or decking, bearings and substructure. Figure 2.1 show a typical bridge component comprises a superstructure and substructure. Superstructure consists of barrier, railing and deck (beam) while substructure consists of piers, abutment and wing wall. Table 2.1 describes in details the components and each of their functions.

With the development of concrete, bridges are being built entirely of concrete, either reinforced or pre-stressed or a combination of both. Most new bridges in Malaysia are made of concrete (King, 2000). In Malaysia, the total number of JKR (Jabatan Kerja Raya) bridges along the state roads is 6647 units the bridges include simple girder, continuous girder, cantilever, arch, bailey, frame, box culverts, suspension and others. In terms of materials of the superstructure, 88% is made of concrete (King , 1999).

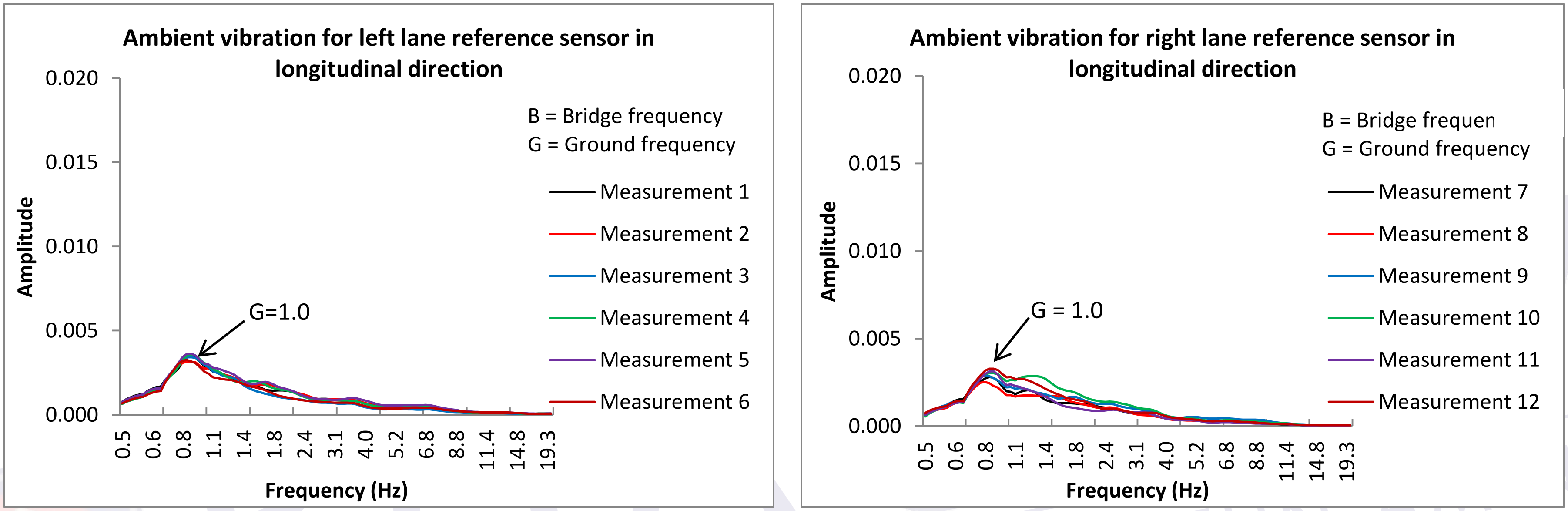


Figure 4.12: Fourier spectra amplitude ratio for left and right lane reference sensor in longitudinal direction of the bridge

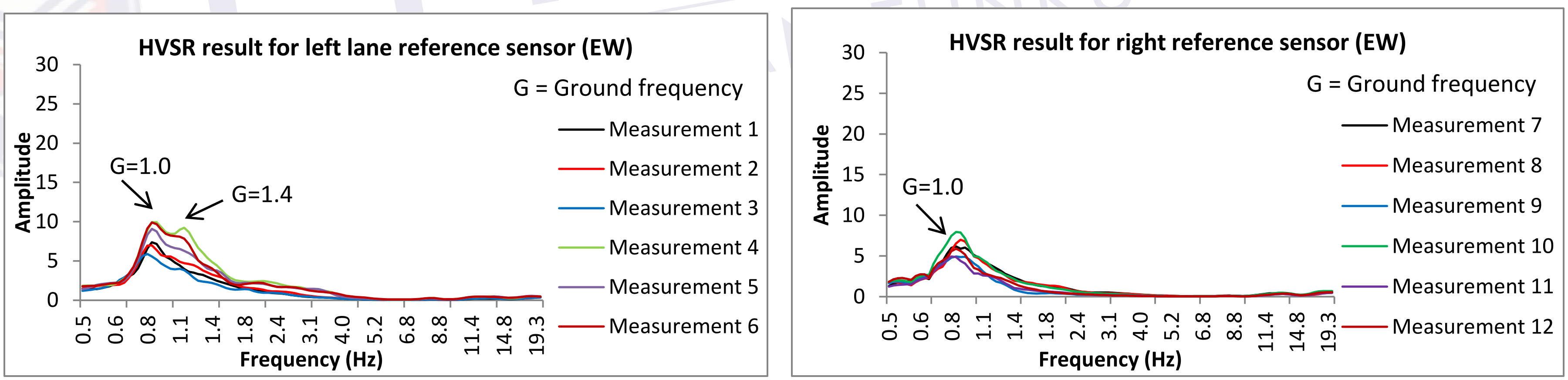


Figure 4.13: Horizontal-to-vertical-spectral-ratio for ground in longitudinal direction.

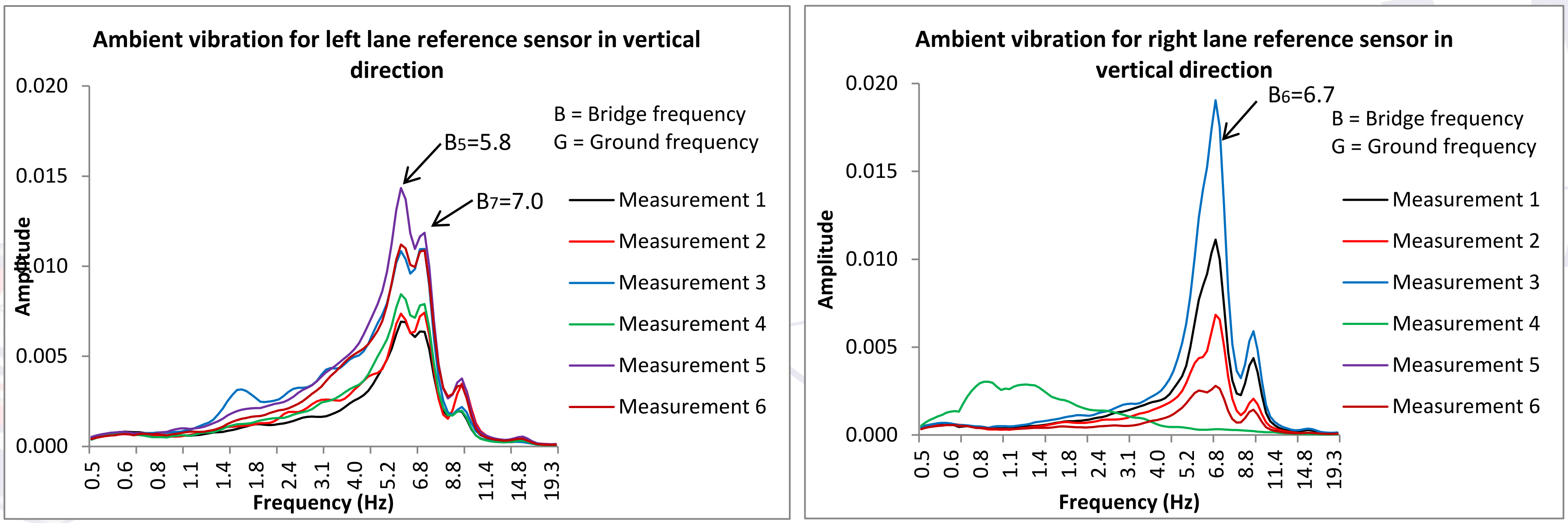


Figure 4.14: Fourier spectra amplitude ratio for left reference sensor in vertical direction of the bridge

4.3.1 Ground natural frequencies

Figure 4.15 shows the HVSR graph for the ground measurement on bridge embankment. The peak values were in the range 1.0 Hz to 1.2 Hz in the North-South and 1.0 Hz to 1.4 Hz in the East-West direction. Figure 4.16 and Figure 4.17 shows the HVSR graph for the ground measurement. From the graph patent, it shows that the natural frequencies of the ground area were in the range 1.0 Hz to 1.3 Hz for the North-South direction and 1.0 Hz to 1.5 Hz for the East-West direction as summarize in Table 4.7.

Table 4.6: Summary of ground natural frequencies

Measurement	Line	Direction	
		NS(Hz)	EW(Hz)
1 & 2	Deck	1.0-1.2	1.0-1.4
3 & 4	A	1.0	1.0
5 & 6	B	1.0	1.0
7 & 8	C	1.0-1.6	1.0-1.3
9 & 10	D	1.1-1.2	1.0-1.5

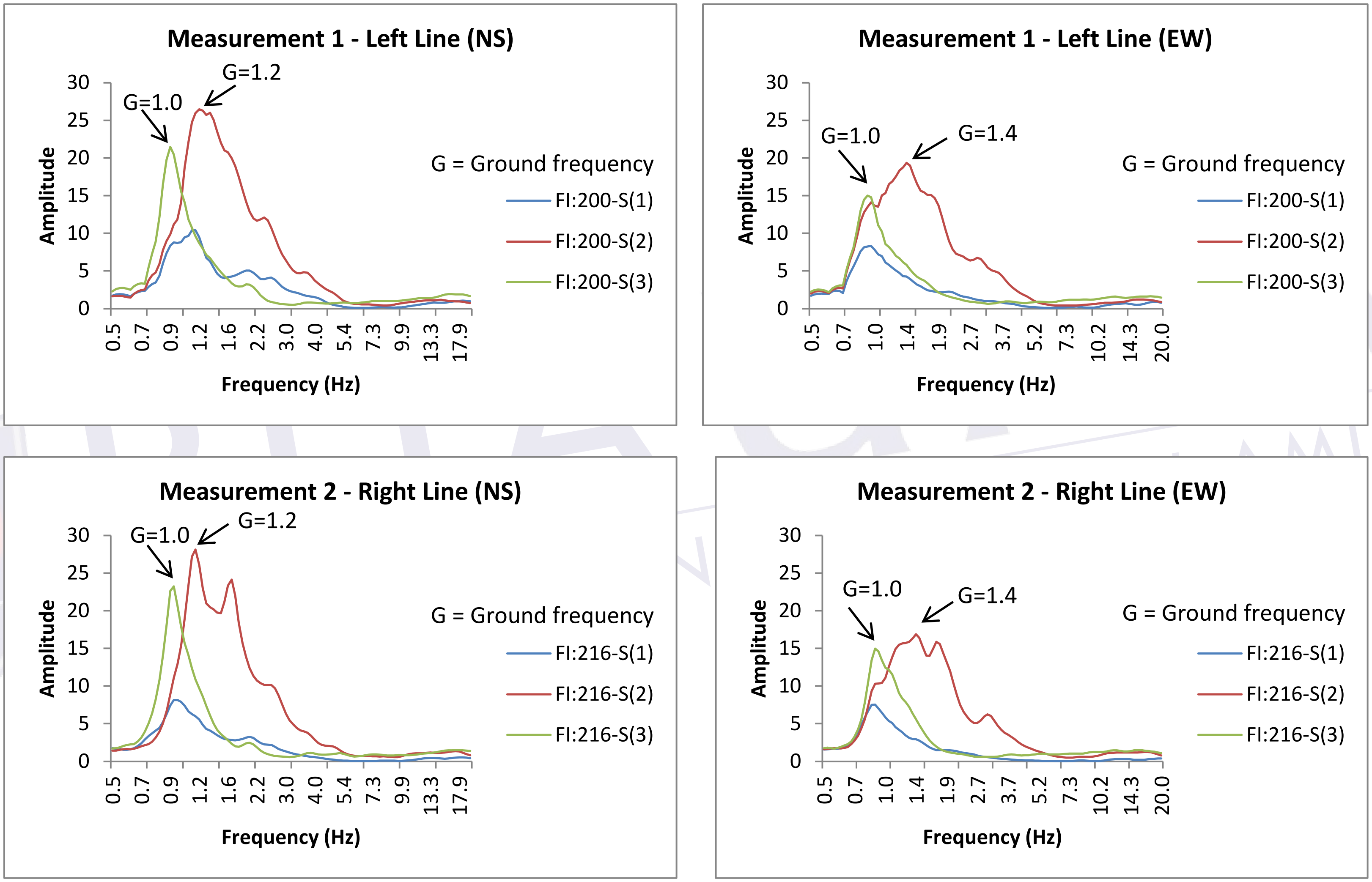


Figure 4.15: HVSR on for measurement along the bridge embankment for left lane and right lane – Sungai Simpang Kiri

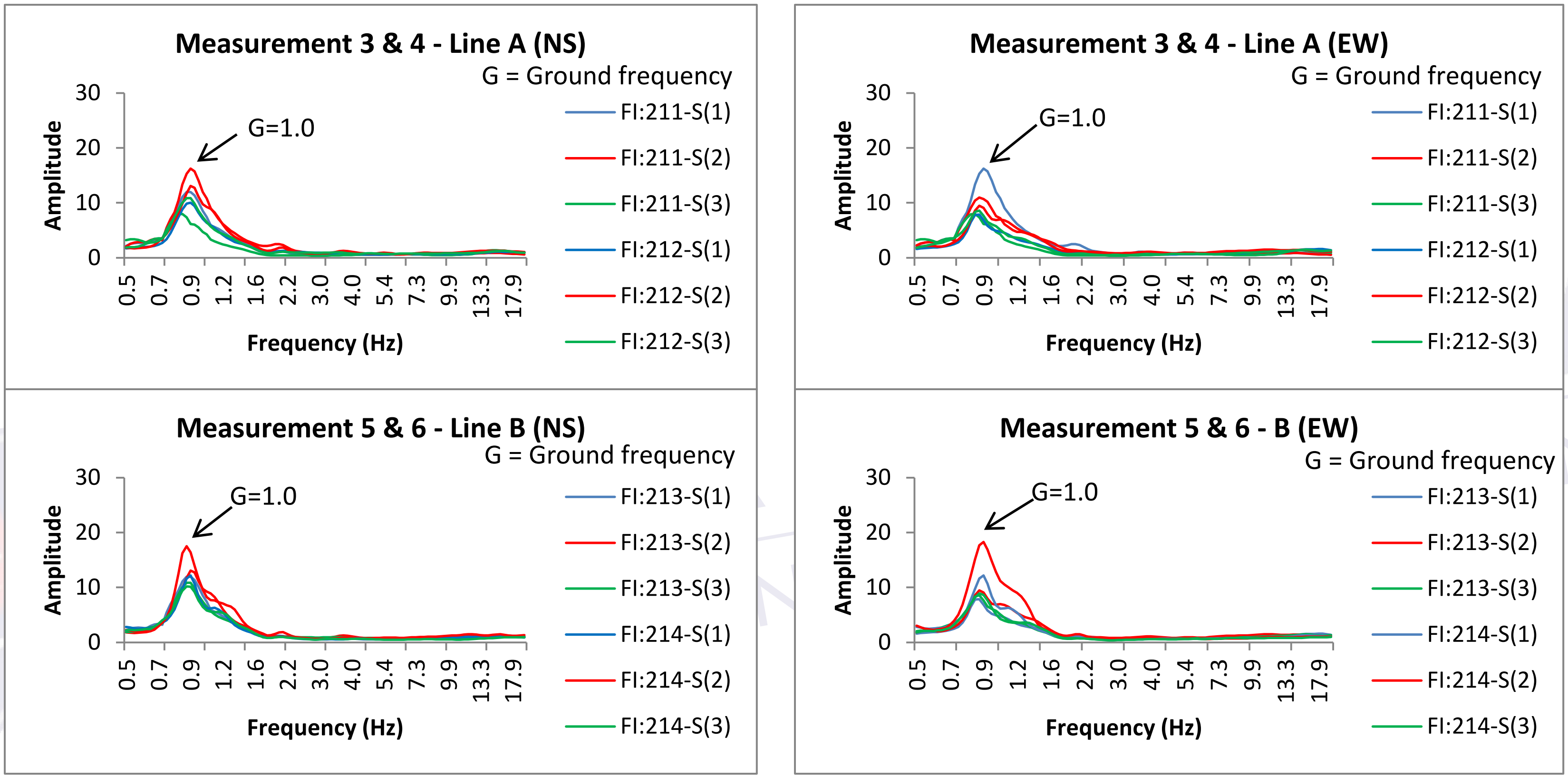


Figure 4.16: HVSR for measurement on ground – Sungai Simpang Kiri

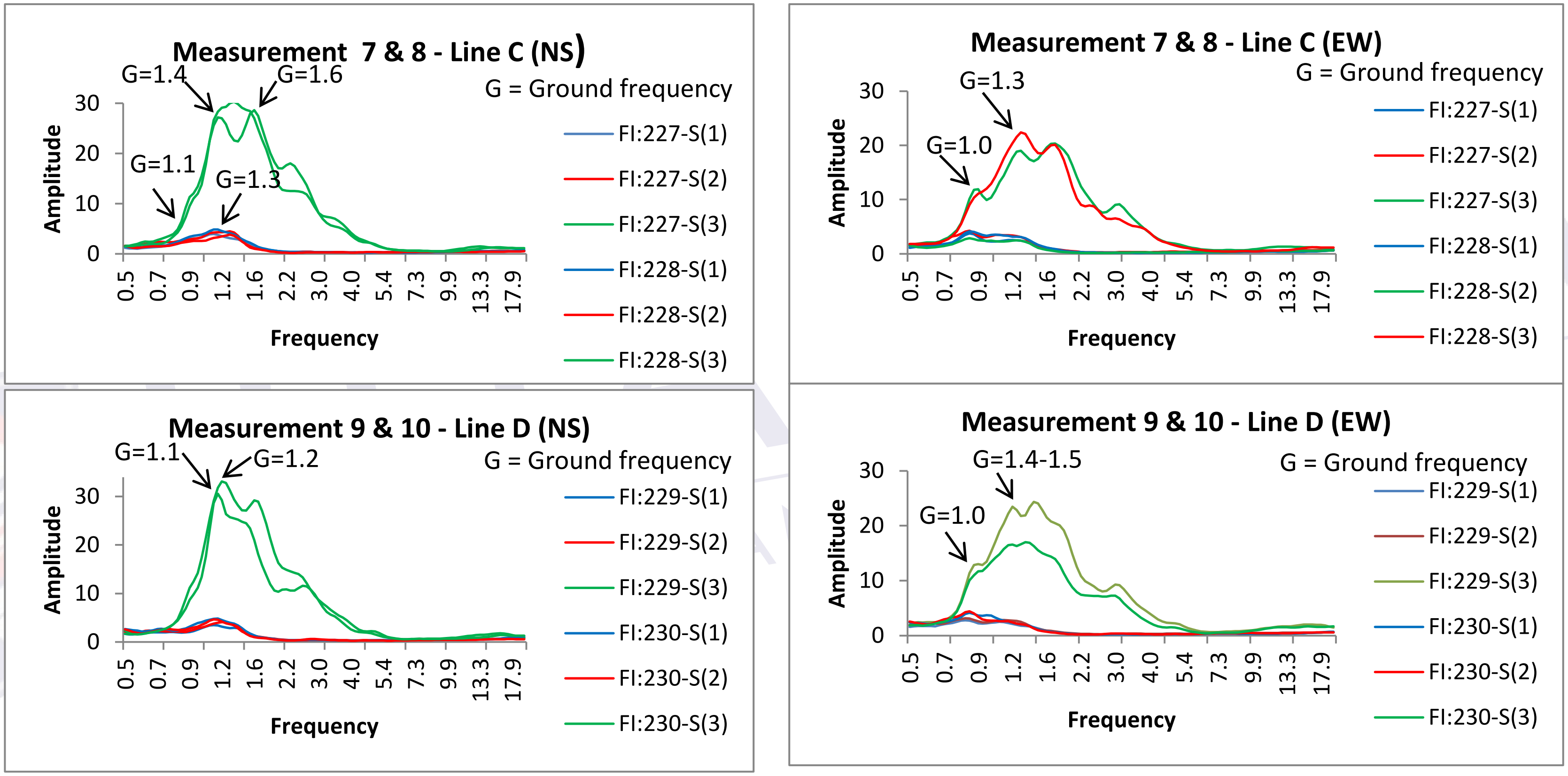


Figure 4.17: HVSR for measurement on ground - Sungai Simpang Kiri

From all the findings it can be concluded there were five modes of natural frequencies for the RC bridge crossing Sungai Simpang Kiri in the range of 2.0 Hz to 7.0 Hz. The first, second and third mode were 2.0 Hz, 2.2 Hz and 2.6 Hz in the transverse direction respectively. The fourth, fifth and sixth mode were 5.8 Hz, 6.7 Hz and 7.0 Hz in vertical direction. On the other hand, the ground natural frequencies were in the range of 1.0 Hz to 1.3 Hz for the North-South direction and 1.0 Hz to 1.5 Hz for the East-West direction.

4.3.2 Comparison bridge natural frequencies and equations provided in the established standards and equation by previous researchers

Table 4.7: Comparison frequency results and empirical equations – Sungai Simpang Kiri

No.	Develop Empirical from Previous Researcher	Fundamental Frequency (calculated), F_1 (Hz)	Fundamental Frequency (measured), Fo (Hz)	$\frac{\text{Calculated}, F_1}{\text{Measured}, F}$
1.	International Union of Railways (1979) from Eq. 2.13	3.0	2.0	1.5
2.	Amman (1995) from Eq. 2.11	3.3	2.0	1.7
3.	Fryba (1996) from Eq. 2.14	2.9	2.0	1.3
4.	British Standard Institution (BS EN 2003) from Eq. 2.15	3.1	2.0	1.4
5.	Microtremor result at Sungai Simpang Kiri	2.0	1.7	1.2

For the Sungai Simpang Kiri bridge, the measurement value was closer to three equations which were by Fryba (1996) and British Standard Institution (BS EN 2003) which were around 30% to 40%. For this bridge, the ratio between manual calculation over measurement was 1.2, a difference of about 20%. The result shows a relative comparable.

4.3.3 Calculation of bridge natural frequency for rc bridge crossing Sungai Simpang Kiri

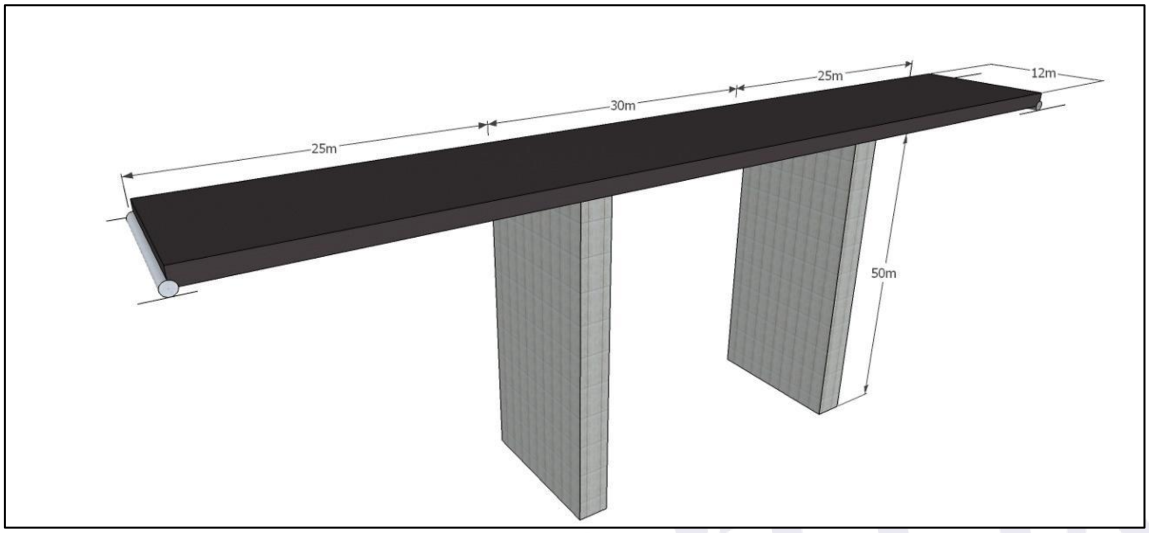


Figure 4.18: RC Bridge crossing Sungai Simpang Kiri dimension

Bridge information:

i) Cross-sectional area of the bridge deck = Length x Width = 70 m x 12 m = 840 m^2

ii) Deck thickness = 0.2 m

iii) Unit weight of concrete, γ = 24 kN/m^2

iv) Elastic modulus of concrete, E_c= 24 kN/mm^2 @ 24 x 10^6 kN/m^2

v) Column Height = 50 m, Diameter of column = 1.2 m

1) Calculating total weight lumped at the deck level

$$W = mg$$

$$\gamma = \frac{W}{V}$$

$$W = 24\ kN/m^2 \times (840\ m^2 \times 0.2\ m) = 4032\ kN$$

2) Calculating corresponding mass

$$m = \frac{4032 \text{ kN}}{9.81 \text{ m/s}^2}$$

$$m = 411.01 \text{ kN-m/s}^2$$

3) Calculating stiffness of the bridge by assuming the bridge deck to displaced rigidly. Each column of the bent behaves as a clamped-clamped column.

For the transversal direction

$$K_{bent} = \sum_{columns} \frac{3EI_c}{h^3}$$

$$= 4\left(\frac{3(24 \text{ x } 10^6 \text{ kN/m}^2)(0.102 \text{ m}^4)}{50^3}\right)$$

$$= 235.01 \text{ kN/m}$$

Two bent provide a total stiffness of, K = 2 x K_{bent} = 2 x 235.01 kN/m = 470.02 kN/m

4) Calculating natural frequency in the longitudinal direction.

$$\omega_n = \sqrt{\frac{470.02 \text{ kN/m}}{411.01 \text{ kN}-\text{m}/s^2}} \qquad = 1.07 \text{ rad/sec}$$

$$f_n = \frac{1.07}{2\pi} \qquad = 1.68 \text{ Hz}$$

For the longitudinal direction, follow step 1 until 2 then continue with step 5 until 6.

5) Calculating stiffness of the bridge by assuming the bridge deck to be displaced rigidly. Each column of the bent behaves as a clamped-clamped column.

$$\text{Second moment inertia, } I_c = \frac{\prod r^4}{4}$$

$$= \frac{\prod(0.6^4)}{4}$$

$$= 0.102 \text{ m}^4$$

$$K_{bent} = \sum_{columns} \frac{12EI_c}{h^3}$$

$$= 4\left(\frac{12(24 \times 10^6 \text{kN/m}^2)(0.102\text{m}^4)}{50^3}\right)$$

$$= 940.03 \text{ kN/m}$$

Two bent provide a total stiffness of, K = 2 x K_{bent} = 2 x 940.03 kN/m = 1880.06 kN/m

6) Calculating natural frequency in the longitudinal direction

$$\omega_n = \sqrt{\frac{K}{M}}$$

$$= \sqrt{\frac{1880.06 \text{ kN/m}}{411.01\text{kN}-\text{m}/s^2}} \quad = 2.1 \text{ rad/sec}$$

$$f_n = \frac{2.1}{2\pi} = 3.36 \text{ Hz}$$

Table 4.9 shows a frequency comparison between calculation and microtremor test with the frequency in the transversal direction was 1.7 Hz, while 2.0 Hz from the microtremor test result. The difference was about 20%.

Table 4.8: Comparison frequency with calculation.

Simpang Kiri Bridge	Frequency (Hz)	
	Transverse	Longitudinal
Calculation	1.7	3.4
Microtremor Test	2.0	-

4.3.4 Comparison between bridge natural frequency and finite element modelling using SAP2000 software.

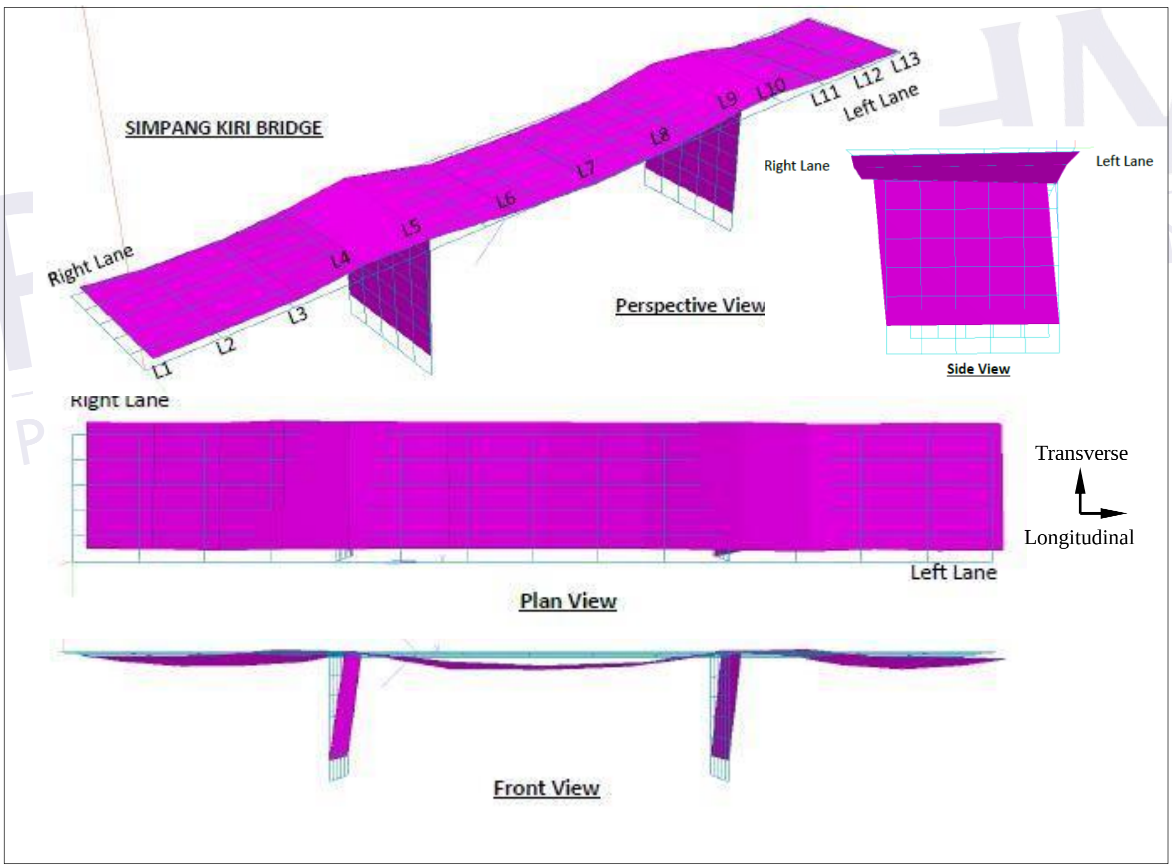
Most researcher used finite element modeling to compare natural frequency values obtained from microtremor test (Idris, Boon, & Kamarudin, 2015). In Kibboua & Farsi (2008), the finite element modeling was developed in order to assess the frequencies and the associated mode of vibration records that will be necessary in the planning of the test on the site (location of the sensors, frequencies to be measured and the mode shapes of vibration. In this study, the natural frequencies from microtremor test were compared with result obtained from SAP2000 by a companion's study that analyzed the same bridge as mode, focusing on the first natural frequency and also first mode of vibration only. The comparison in frequency values as shown in Table 4.9.

The natural frequency from the microtremor test was 2.2 Hz whereas from SAP2000 was 1.9 Hz. The frequency value was relatively comparable for the first mode. Starting form the second mode onward the frequencies value and mode shape is different.

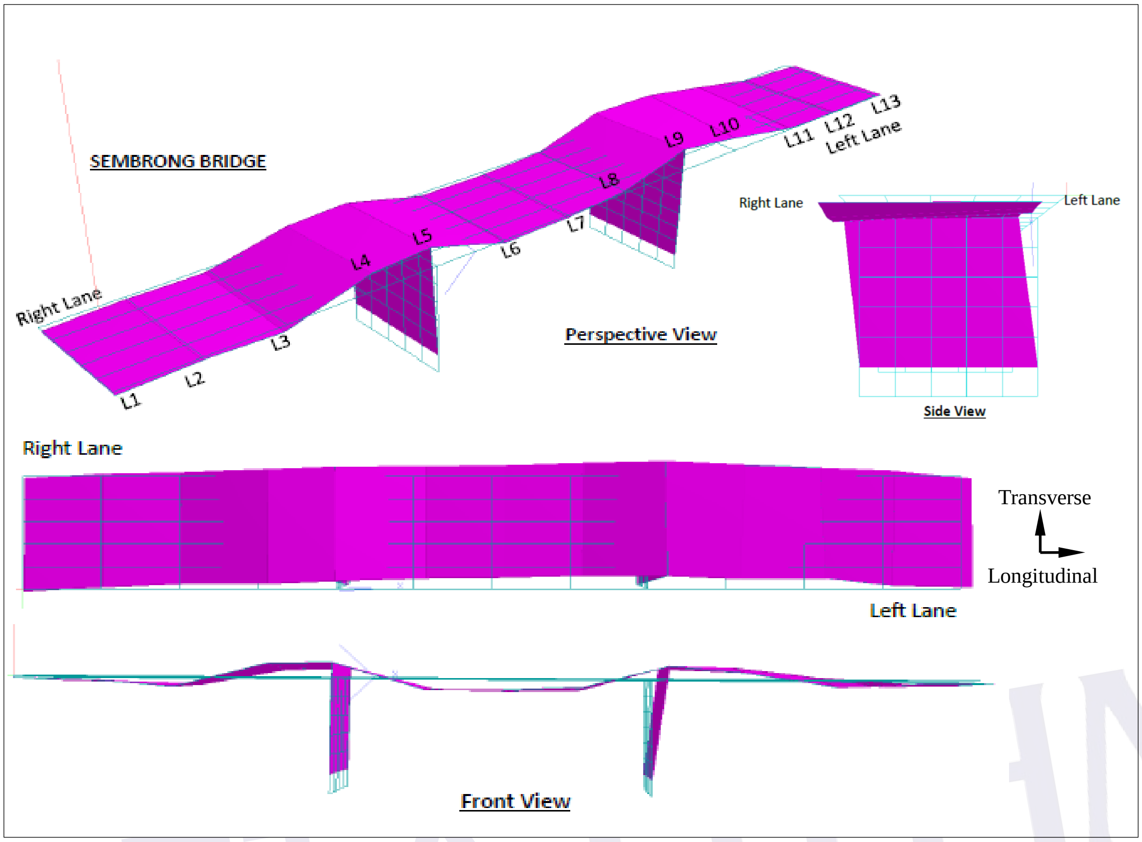
Table 4.9: Comparison of frequencies with the SAP2000 results

Mode of frequencies	SAP2000 modelling (Yusoff *et al.*, 2016)	Microtremor Test
1	1.9 Hz (transverse)	2.2 Hz (transverse)
2	2.2 Hz (transverse)	3.0 Hz (longitudinal)
3	3.4 Hz (vertical)	3.3 Hz (longitudinal)
4	6.4 Hz (vertical)	3.3 Hz (transverse)
5	6.5 Hz (vertical)	4.0 Hz (longitudinal)
6	6.6 Hz (transverse)	4.2 Hz (longitudinal)

Mode shape for the measure bridges as shown in Figure 2.19 plotted using STAAD Pro software. Both bridges have the same pattern mode of vibration which is in transversal direction. The transversal direction is also the weakest direction of the bridge which means the bridge will be more affected from the ground motion from the transversal direction. Whereas, the mode shape from the SAP2000 software as shown in Figure 4.20. The first mode shape is also in the transversal direction. The frequency value of the finite element modeling is smaller compare to measurement value. In other word, mean that the bridge is stiffer compare to the actual bridges condition. The model could be improved by considering the realistic nature of bridge boundary condition and also permissible degrees of freedom (Kibboua & Farsi, 2008). It can be concluded that the value from microtremor result is comparable with finite element modeling result.



a) Sungai Simpang Kiri



b) Sungai Sembrong

Figure 4.19: Mode Shape from microtremor test (a) Sungai Simpang Kiri

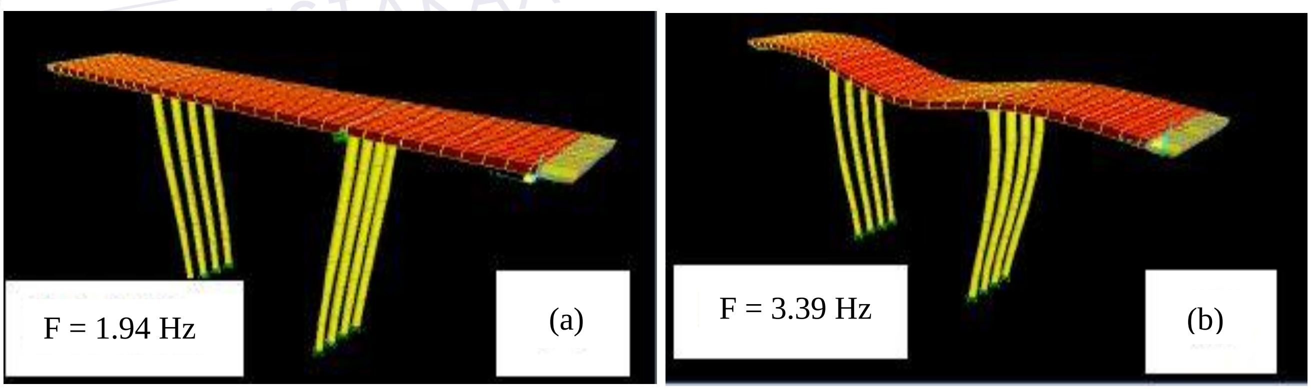


Figure 4.20: Mode Shape from SAP2000 (a) Transverse direction , (b) Vertical direction (Yusoff *et al*., 2016)

functions primarily as the mass and stiffness characteristics and their distribution in the structure, the boundary conditions of the structure and the connectivity or continuity conditions between the various subcomponents of the structure (Grimmelsman, K.A., 2006). The first mode frequency is the one on the lowest energy level and is the most likely to be activated (Hivos, 2007).

As a conclusion, the fundamental frequency of the bridge depends on the span length, type of bridge construction, mass, stiffness, distribution in the structure and also the boundary condition.

Table 4.10 : Summary of study results

Bridge	Sungai Sembrong Bridge	Sungai Simpang Kiri Bridge
Span Length	75 meter (25m+25m+25m)	70 meter (20m+30m+20m)
Fundamental frequency	2.2 Hz	2.0 Hz
Mode of vibration	Transverse direction (weakest direction for the bridges due to ground motion)	
Ground natural frequencies	1.4 Hz to 1.6 Hz (N-S) 1.4 Hz to 2.1 Hz (E-W)	1.0 Hz to 1.3 Hz (N-S) 1.0 Hz to 1.5 Hz (E-W)
Frequency result verification	a) Manual Calculation b) Develop empirical equation from previous researchers c) Code of practice d) Finite element modeling results from companion's study Yusoff *et al.* (2016) for Sungai Kangkar Merlimau Bridge only.	

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main findings in this research are highlighted in the following section. Microtremor test was conducted on two different lengths of simple supported bridges to observe the frequencies patents. Both bridges have the same number of span (3 spans). The frequency values for both bridges were almost the same. The natural frequency for Sungai Sembrong Bridge is 2.2 Hz and Sungai Simpang Kiri Bridge is 2.0 Hz. Sungai Simpang Kiri Bridge have a lower frequency value compare to Sungai Sembrong Bridge due to the longer maximum span length which is 30 meter, 5 meter longer than Sungai Sembrong span length which is 25 meter. The mode of vibration for both bridges is in transversal direction. This direction is the weakest direction for the bridges due to ground motion.

For the ground natural frequencies, it can be concluded that the ground natural frequency for Sungai Sembrong site are in the range of 1.4 to 1.6 Hz for the North-South direction and 1.4 Hz to 2.1 Hz for the East-West direction. Meanwhile, for Sungai Simpang Kiri, the ground natural frequency are in the range of 1.0 Hz to 1.3 Hz for the North-South direction and 1.0 Hz to 1.5 Hz for the East-West direction. The first natural frequency results were verified by calculating and, developing empirical equations from previous researchers, code of practice and finite element modeling results from a companion’s study on the same bridge. The results shows the identified frequencies can be acceptable.

As a conclusion, overall objectives of this study were achieved. This study can be used as a preliminary assessment of dynamic characteristic of existing bridges. Identification of bridges natural frequencies can be used to monitor resonance phenomena in the study area. This study can also be used widely for different types of bridges as a dynamic characteristics record for new bridges to be constructed using seismic code since the testing is able to be conduct an accurate and reliable data gathering.

5.2 Recommendations

1) Repeated measurements need to be conducted at different times. This is to ensure the reference sensor does not record the microtremor signal continuously in case of limited amount of sensor available. This situation also makes the variation in terms of amplitude of the recorded signal only not to the frequency.
2) A total of 8 hours is required to complete the necessary records for each bridges measurement. However, a longer time for recordin of each record will give more relevant microtremor record.
3) Testing needs to be conducted during less traffic crossing a bridge in order to get a valid microtremor signal and also to avoid the presence of noise having dominant frequencies that could be involved in the vibration modes.
4) Guide from a well-trained operator is needed. The achieved operations were not simple and easy while conducting the test without expert guide. This fact was due to the topography at the location of the bridge and the difficulties to places sensors on the deck surface bridge as well as the problem faced when using the equipment during the tests. There are also the potential problem of the presence of noise having dominant frequencies that could be involved in the vibration modes, especially when the sensors are not well positioned and oriented.

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